Construction and Building Materials 143 (2017) 429–443

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental and numerical investigation of static and fatigue behavior of mortar with blast furnace slag sand as fine aggregates in air and water

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HIGHLIGHTS

- Static and fatigue behavior of mortar with BFS sand is investigated in air and water.
- Stress-strain relationships for BFS and CS mortar are developed under static loading.
- Simplified fatigue model is proposed for the assessment of plastic strain, total strain and fracture parameter.
- Fatigue life of BFS and CS mortar is predicted at different stress levels using the proposed fatigue model.

ARTICLE INFO

Article history:
Received 9 December 2016
Received in revised form 11 March 2017
Accepted 16 March 2017

Keywords:
Mortar
Blast furnace slag sand
Fatigue
Air
Water
Stress-strain model
Simplified fatigue model

ABSTRACT

The experimental and analytical study are attempted to clarify the static and fatigue behavior of mortar with blast furnace slag (BFS) sand as fine aggregates in compression in air and water. The cylindrical BFS mortar specimens were used for static and fatigue compression tests in air and water and results are compared with those of mortar using crushed sand (CS). The fatigue load was applied in the form of sine signal with a constant amplitude and the frequency of 5 Hz. The stress level is varied from 60%, 70% and 80% of the uniaxial compressive strength. The experimental results disclose that BFS mortar exhibits more fatigue life compared to CS mortar in air, while it is similar in water. Thereafter, the stress-strain relationships for each mortar under monotonic loading are formulated. Moreover, a simplified fatigue model for the assessment of plastic strain, total strain and fracture parameter at different number of loading cycles and for prediction of fatigue life is also proposed.

1. Introduction

Cementitious materials, mainly in the form of concrete are the most widely used construction material in the world because of easy availability of its constituent materials and unique properties; every year more than 1 m^3 of concrete is produced per person worldwide [1,2]. However, the sustainability and durability of reinforced concrete structures are still the main issues because of their exposure to a variety of loading including environmental and mechanical actions. Various approaches have been used to enhance the durability of concrete like using steel fibers, mineral admixtures and industrial wastes. Due to environmental considerations and strict regulations, numerous research is being carried out to use industrial wastes in concrete industry because it will not only reduce the need to landfill these wastes, but it will also minimize the environmental loads, energy consumption and depletion of natural resources [3]. Moreover, the usage of industrial wastes in concrete would be a feasible option considering the economy compared to steel fibers and admixtures. Blast furnace slag is among one of such industrial wastes; generated during the production of iron and steel. This slag is a by-product obtained by quenching molten iron slag from blast furnace in water or steam to produce glassy and granular product that is then dried and ground into fine powder or sand particulates. In Japan, volume of granulated blast furnace slag produced is over 20 million tons per annum and 90% of it is used as a material for cement and concrete production [4].

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http://dx.doi.org/10.1016/j.conbuildmat.2017.03.147
0950-0618/

Concrete containing granulated blast furnace slag (GBFS) is well known for improving its properties due to pozzolanic activity of GBFS resulting in dense matrix, high strength at long-term age and better durability properties like water tightness, chemical resistance and chloride ion permeation [3,4]. In the previous studies, the ground granulated blast furnace slag (GGBFS) has been used as percentage of cementitious materials with the maximum percentage replacement of binder with GGBFS as 50% in concrete because the higher proportion of GGBFS can impair the 28 days compressive strength of concrete [5]. Valcuende et al. (2015) studied the properties of concrete with GBFS sand as percentage of fine aggregates and found that early age compressive strength of concrete with GBFS sand is almost similar to the concrete with river sand, but the compressive strength improves at longer age with increased replacement of fine aggregates by slag [6]. On contrary, it is pointed out that high quantity of non-ground GBFS as fine aggregates results in high porosity and less compressive strength of concrete [7,8]. However, in the recent years, it has been found that the durability related properties of mortar and concrete can be greatly improved by the use of GGBFS as percentage of binder and with the incorporation of BFS as total amount of fine aggregates. It is reported that the mortar and concrete containing BFS fine aggregates show significant resistance against various severe environmental actions like frost damage and corrosion [9,10]. In addition, significant improvement in resistance was observed when mortar and concrete with BFS were exposed to sulfuric acid compared to ordinary one [11]. However, the mechanical characteristics of BFS mortar and concrete are not clarified yet. To apply such material in reinforced concrete (RC) structures subjected to mechanical loading, it is essential to have relevant understanding of the various conditions that ensures durable concrete performance so that the design method for structures with such concrete can be developed. Especially, the evaluation of fatigue performance of such mortar and concrete is vital because the failure of concrete structures subjected to repetitive loading takes place at stress level much lower than the ultimate compressive strength due to propagation of microcracks generated at the interfacial transition zone of cementitious matrix and aggregates. Thus, as a first step, the investigation is carried out to study the mechanical behavior of mortar with BFS fine aggregates under static and fatigue loading. Moreover, some of the RC structural elements like piers are always submerged in water and RC bridge deck slabs also get saturated occasionally due to penetration of rain water through cracks in the asphalt wearing surface. Therefore, it is necessary to elucidate the behavior of mortar and concrete not only in air but also in water.

This paper demonstrates the experimental investigation carried out to study the uniaxial compressive static and fatigue performance of mortar with BFS sand in compression compared with ordinary mortar containing crushed sand (CS) in air and water. Fatigue life at different stress levels is evaluated and the damage progress is discussed based on the strain development. Thereafter, the stress-strain relationships for both types of mortar are formulated under monotonic loading in air and water. Moreover, a simplified fatigue model is proposed to assess the plastic strain, total strain and change in fracture parameter under cyclic loading and for the prediction of fatigue life of each mortar in air and water.

2. Experimental details

2.1. Materials

Two series of mortar specimens were casted, blast furnace slag (BFS) mortar and crushed sand (CS) mortar. Ordinary Portland cement (OPC) was used as binder in both types of mortar. The density of ordinary Portland cement is 3.15 g/cm^3, while the Blaine fineness is 3300 cm^2/g.

In the preparation of BFS mortar specimens, BFS sand is used as full amount of fine aggregates which is cooled rapidly by pressurized water jets after it is ejected from blast furnace at 1500 °C, then it is granulized into required size. Granulated blast furnace slag has an amorphous structure containing a large amount of silica and alumina and it shows pozzolanic properties when it is ground to very fine size. For CS mortar specimens, crushed river sand is used as fine aggregates. Fine aggregates with particle size of 0.3–5 mm are used in this study. The physical properties of fine aggregates are given in Table 1.

Table 1
Physical properties of fine aggregates.

Property	Crushed sand	Blast furnace slag sand
Saturated density (g/cm^3)	2.65	2.72
Fineness modulus	2.96	2.23
Water absorption (%)	1.97	1.12

2.2. Mix proportions and specimen preparation

Table 2 presents the mix proportion of BFS mortar and CS mortar. The cement to sand ratio is kept as 1:2 with water to cement ratio of 35% for both types of mortar. The polycarboxylate type of high range water reducing admixture is used as an additional admixture. Various researches show that with the use of high range water reducing admixture, excessive air bubbles are formed inside the mortar decreasing the surface tension during liquid phase [12]. Therefore, the antifoaming agent is used to control the air content inside the mortar.

One batch for each BFS mortar and CS mortar was prepared. The cylindrical specimens were casted with diameter of 50 mm and height of 100 mm in steel molds for each type of mortar. After demoulding, the specimens were cured in normal water for seven days. The top casted surface of the cylindrical specimens was ground to make it smooth and parallel to the hinge surface placed between loading platen and specimen. For strain measurement, two vertical and two horizontal strain gauges of 30 mm gauge length were attached to the surface of cylindrical specimens. The vertical and horizontal strain gauges were attached parallel and perpendicular to the axial loading direction respectively using epoxy resin.

2.3. Test method

2.3.1. Static compression test

The uniaxial static compression tests were carried out on three cylindrical specimens of each BFS mortar and CS mortar in air at

Table 2
Mix proportions of blast furnace slag mortar and crushed sand mortar.

Mortar type	W/C (%)	Unit content (kg/m^3)				HRWRA (kg/m^3)	AFA (kg/m^3)
		W	C	BFS	CS		
BFS	35	268.5	767	1533	0	3.84	2.30
CS		271.6	776	0	1552		

BFS. Blast furnace slag, CS: Crushed sand, W: Water content, C: Ordinary Portland cement, HRWRA: High range water reducing admixture, AFA: Antifoaming agent.